

Application No. 10/016,870
Reply to the Office Action mailed Sept. 21, 2005

REMARKS/ARGUMENTS

Claims 1-6, 9 and 12-19 remain in the application. Claim 12 and 14-19 have been amended. Claim 13 has been cancelled.

Claim Rejections - 35 USC § 112

The rejection of claims 1-19 under 35 USC § 112, first paragraph, was maintained by the Examiner. Particularly, the Examiner believes that the specification fails to teach how the maximum void size is determined such that flame propagation therethrough is limited, and that the teachings of US 6,494,189 and US 4,013,190 do not allegedly provide sufficient guidance as to how to so determine maximum void size.

Applicant respectfully believes that this information (i.e. the minimum distance required for a flame front to be generated and to propagate, and therefore the void size necessary to quench any such flame) is in fact a concept well understood in the art. This basic concept is employed in many applications, including the oil and natural gas industry for example, which use pipeline flame arrestors to ensure flames don't propagate within the pipeline. Such flame arrestors typically comprise a plurality of narrow passages, through which the oil/natural gas can flow but which prevent flame fronts from passing therethrough. See for example the crimped ribbon type flame arrestors of US patents 4,909,730 and 5,415,233.

The Examiner alleges that the teachings of US 6,494,189 and US 4,013,190 are directed to flame arrestors which employ an open cell foam material, rather than the fibrous matrix of the present invention, and thus fail to teach how the size of pores without the fibrous matrix are to be selected. With respect, the concept of arresting flame propagation by sizing apertures such that they are less than the MSEG (Maximum Safe Experimental Gap – see definition below) based on the type of fuel and material, is well known in the art. Therefore, although the materials may differ, the concept and manner of determining such MSEG remain the same.

The Applicant invites the Examiner to consider the following documents, which deal with quenching distances for flame fronts and how to calculate/determine flame quenching distances, and therefore distances of void size which below which flame will be unable to propagate.

1) N.A.C.A. Report 1264, by *A. E. Potter, Jr. A. I. Berlad*,
Jan. 1956

A copy of this report is enclosed herewith.

Generally, this NACA/NASA technical paper from 1956 describes an approximate thermal equation which was derived for flame quenching distance. The quenching distance was expressed in terms of the thermal conductivity, the fuel mole fraction, the heat capacity, the rate of the rate-controlling chemical reaction, a constant that

Application No. 10/016,870
Reply to the Office Action mailed Sept. 21, 2005

depends on the geometry of the quenching surface, and one empirical constant. The effect of pressure on quenching distance was shown to be inversely proportional to the pressure dependence of the flame reaction, with small correction necessitated by the effect of pressure on flame temperature. The quenching distance was shown to be inversely proportional to burning velocity and pressure at any given initial temperature and equivalence ratio.

2) The Glossary on Explosion Dynamics from the Aviation Kerosene (Jet A) Research lab at Caltech University.

Web site link: <http://www.galcit.caltech.edu/EDL/projects/JetA/Glossary.html>

The Applicant would like to particularly point out the definitions for *MSEG* and for *Quenching Distance*, reproduced below:

Maximum Safe Experimental Gap (MSEG) A flame can be initiated in the explosive atmosphere even when the height of a channel or gap connecting the ignition chamber with the explosive atmosphere is smaller than the laminar flame quenching height. Even after a flame stops actively propagating, there may still be sufficiently hot products and radical species to restart flame propagation when the products emerge from the channel and the loss mechanism, heat transfer to the channel walls, is removed. This was first observed experimentally when developing standards for gaps in enclosures of electrical equipment. The maximum gap height that prevents explosion transmission can be a factor of two or smaller than the laminar flame quenching diameter. Standardized tests have been developed to measure the MSEG and are used to certify "explosion-proof" electrical enclosures.

Quenching Distance - A characteristic length scale associated with laminar flame quenching during propagation in a narrow channel or tube. The minimum height of a channel in which a hydrocarbon-air flame can propagate at NTP is about 1.6 mm for mixtures with equivalence ratios between 1 and 2. The minimum diameter of a tube is about 2 mm. This distance varies inversely with initial pressure and is smaller for mixtures with higher laminar flame speeds. Turbulent explosions can be transmitted through openings smaller than the laminar flame quenching distance.

Therefore, it is clearly a well known concept that a flame requires a given distance to propagate (i.e. the MSEG), and therefore that if a void or opening within which the flame may originate is sized smaller than this given distance the flame will be quenched, regardless of whether the material is an open cell foam, a fibrous matrix, or another such material.

Therefore, the Applicant respectfully believes that reconsideration and withdrawal of the rejection of claims 1-19 under 35 USC § 112, first paragraph, is warranted.

Claim Rejections - 35 USC § 102 / 103

Claims 1-2, 4, 9, 12-13 and 15-19 were rejected under 35 USC § 102(b) as being anticipated, or in the alternative under 35 USC § 103(a) as being rendered obvious, by Puech (GB 384,930).

Application No. 10/016,870
Reply to the Office Action mailed Sept. 21, 2005

Puech discloses a *cowling* for an aircraft engine (i.e. not an aircraft engine itself), which has air vent openings therein that are partially covered by a triple layered covering which is said to prevent flames from a fire which originates within the cowling from escaping and also is said to enable the extinction thereof.

Applicant would like to point out the following definition of "cowling" as per the *Merriam-Webster Collegiate Dictionary*, 10th ed. :

"a removable metal covering that houses the engine and sometimes a part of the fuselage or nacelle of an airplane; also : a metal cover for an engine"

Accordingly, a cowling as taught by Puech cannot be read to include the engine itself, but rather defines a compartment within which an engine is housed. Fig. 1 of Puech supports this definition and construction. The Examiner is not entitled to give the term cowling a definition different from that commonly understood in the prior art and as defined in the specification of Puech itself.

Therefore, it cannot be said that Puech teaches a gas turbine engine, having a hot section which includes a combustion chamber therein and an outer casing (i.e. of the gas turbine engine) surrounding the hot section, as per the present invention as claimed. Therefore, Puech fails to teach or suggest the use of the "triple covering" anywhere but in the vent openings of an aircraft cowling. Regardless of the structure of the triple covering, Puech failed to recognize the advantage of locating a flame arresting member directly on the engine casing, such as to prevent fires from even beginning. Instead, Puech tries to contain such engine fires without a surrounding cowling. This is clearly much less desirable, as the engine and the internals of the cowling (including electrical systems, etc.) would be exposed to such a cowling fire. Puech therefore fails to either anticipate or render obvious the present invention as claimed in independent claims 1 and 12 at least for this reason alone.

The triple layer covering, which Puech applies within the ventilation openings of the cowling, is said to impede the advance of fire which has broken out around the engine (within the cowling), to localize the flames to their point of origin (i.e. within the cowling), and to enable extinction thereof. This fire arresting triple covering disposed within the cowling's vent openings is therefore intended to contain and help extinguish a fire *which has already started*, for example one which has broken out around the engine and must be contained within the envelope of the cowling, and not be permitted to pass out through the openings of the cowling. Puech's intent is therefore to prevent the flames from passing through such openings in the cowling. The present invention, in contrast, is aimed at quenching any spark (i.e. preventing a flame from even starting) directly at its point of origin on the engine casing surface itself. The fire retarding member of the present invention is therefore located directly on the surface of the hot engine casing, such as to prevent fires from starting rather than trying to contain and/or extinguish them once they have already begun as per Puech. The fire retarding member of the present invention therefore limit large voids,

Application No. 10/016,870
Reply to the Office Action mailed Sept. 21, 2005

either within itself or between itself and the engine casing, such as to prevent such a propagation of flame within the surrounding cowling, which Puech allows to occur.

With respect to the Examiner's suggestion that a percent density of between 10-30 % would be inherent to the device taught by Puech, this is clearly false. Nothing taught or suggested by Puech, in describing the triple layered covering, suggests any such range of density of the fire retarding element. Merely because Puech discloses three layers, each having a different construction, does not explicitly or implicitly suggest any desirability, advantage or reason why such a density is either possible or sought. Therefore, the Examiner is unjustified in alleging, in hindsight, that Puech discloses the claimed properties merely because the fire screen taught by Puech also attempts to contain/extinguish fire and because the three layers are made of various porous materials.

With respect to claim 18, Puech fails to teach or even suggest that the triple covering disposed within the ventilation openings of the cowling is flexible or extensible (in any direction), and therefore it cannot be fairly said that Puech discloses that the triple covering is un-extendable in a direction substantially parallel to the engine casing. As no teaching or suggestion in this regard is made, Puech does not anticipate or render obvious claim 18.

Accordingly, the rejection of claims 1 and 12 under 35 USC § 102(b) or 103(a) as being anticipated or rendered obvious by Puech is unsupported, as should be withdrawn, as Puech fails to disclose each and every element of claims 1 and 12. For the reasons above, dependent claim 16 is similarly novel and non-obvious over Puech. At least in view of their dependence on claims 1 and 12, claims 2, 4, 9, 15-19 are also believed to be novel and non-obvious in view of Puech.

The Applicant therefore submits that claims 1 and 12 are both novel and non-obvious over Puech, and that all dependent claims, including claim 2, 4, 9 and 15, are similarly novel and non-obvious. Reconsideration of their rejection under 35 U.S.C. § 102(b) or 103(a) is therefore respectfully requested.

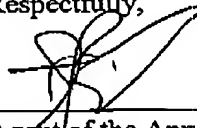
Claim 3 was further rejected 35 U.S.C. § 103(a) as being obvious over Puech in view of McCullough (US 4,844,974). Claims 5-6 and 14 were rejected under 35 U.S.C. § 103(a) as being obvious over Puech in view of Nevin (GB 2,266,051). In view of the claims as presently submitted, the comments above and at least in view of the dependence of claims 3 and 5-6 on claim 1 and the dependence of claim 14 on claim 12, the subject matter of these dependent claims is believed to be neither taught nor suggested by Puech, McCullough or Nevin, either alone or in combination. Reconsideration is therefore respectfully requested.

It is submitted therefore that claims 1-6, 9, 12 and 14-19 are now in condition for allowance. Reconsideration of the Examiner's rejections is respectfully requested.

Application No. 10/016,870
Reply to the Office Action mailed Sept. 21, 2005

In the event that there are any questions concerning this amendment or the application in general, the Examiner is respectfully urged to telephone the undersigned so that prosecution of this application may be expedited.

Respectfully,



January 23, 2006

Date

Agent of the Applicant

T. James Reid, Reg. No. 56,498

OGILVY RENAULT LLP

Customer No. 32292

CERTIFICATE OF FACSIMILE TRANSMISSION

I hereby certify that this paper is being facsimile transmitted to the United States Patent and Trademark Office on the date shown below.

T. James Reid, Reg. No. 56,498

Name of person signing certification



Signature

January 23, 2006

Date

REPORT 1264

A THERMAL EQUATION FOR FLAME QUENCHING¹

By A. E. POTTER, Jr., and A. L. BERLAD

SUMMARY

An approximate thermal equation was derived for quenching distance based on a previously proposed diffusional treatment. The quenching distance was expressed in terms of the thermal conductivity, the fuel mole fraction, the heat capacity, the rate of the rate-controlling chemical reaction, a constant that depends on the geometry of the quenching surface, and one empirical constant.

The effect of pressure on quenching distance was shown to be inversely proportional to the pressure dependence of the flame reaction, with a small correction necessitated by the effect of pressure on flame temperature.

The equation was used with the Semenov equation for burning velocity to show that the quenching distance was inversely proportional to burning velocity and pressure at any given initial temperature and equivalence ratio.

In order to use the equation with experimental data, the rate-controlling reaction must be specified. Two choices were made: (1) the reaction between active particles and fuel (corresponding to the diffusional equation), and (2) the reaction between oxygen and fuel.

The two equations, one based on the active-particle-fuel reaction, the other based on the oxygen-fuel reaction, were tested using published data for the quenching of propane-oxygen-nitrogen flames. The data selected included the effect on quenching distance of oxygen-nitrogen ratio, propane concentration, and initial mixture temperature and pressure. A correlation of these data was obtained using each of the two equations, although both possessed shortcomings. The equation using the active-particle-fuel reaction did not correlate data for all rich mixtures; the equation using the oxygen-fuel reaction, while correlating data for both rich and lean mixtures, showed a larger deviation from the predicted linear relation than the other equation.

INTRODUCTION

The process of flame quenching is of interest, since it may be related to other combustion phenomena of engineering importance, such as flame stabilization, flammability limits, and the general behavior of flames near cold walls. Flame-quenching processes become especially important in turbojet combustion systems when operation at low pressure (i. e.,

high altitudes) is considered. Flame quenching is usually studied experimentally in terms of the quenching distance, which is defined as the minimum channel size that will allow a given flame to propagate. Most of the available quenching data have been obtained either by (1) observation of the minimum tube diameter or rectangular slot width that will allow a flame to flash back, or by (2) determination of the minimum distance between plane-parallel plates that will allow a flame to propagate from a spark of minimum ignition energy.

A rigorous theoretical treatment of the quenching process appears to be a most difficult task (refs. 1 and 2). Consequently, present theoretical treatments of quenching are necessarily approximate and seek primarily to correlate the quenching process with the variables that affect it, such as pressure, temperature, fuel type and concentration, inert-gas concentration, and quenching-surface geometry.

Approximate treatments of quenching have been based either on a thermal or a diffusional mechanism for the process (refs. 3 and 4). Such apparently different outlooks yield results consistent with experimental data because the equations for heat and mass transfer are formally identical, and because the thermodiffusivity and the molecular diffusivity are numerically nearly equal (ref. 5). Thus, each purely thermal approach to a combustion process has a diffusional analog.

A quenching-distance equation that successfully correlates lean quenching data (refs. 4, 6, and 7) is the diffusional equation given in reference 4. Unfortunately, the use of this equation in its present form is limited to stoichiometric or lean mixtures. The source of this difficulty appears to be the choice of the reaction kinetics.

Essentially, the objective of this paper is to extend, if possible, the useful range of the quenching concepts of reference 4 to include hydrocarbon-rich mixtures. Because of the similarities between heat and mass flow, it is to be expected that a thermal analog equation can be derived that will correlate data equally as well as the diffusional equation of reference 4. It is felt that such an alternate thermal equation is more susceptible to changes in the reaction kinetics than the original diffusional model. The result of such changes is an extension of the useful range of fuels and oxidants that may be treated.

¹ Supersedes NACA TN 3368, "A Thermal Equation for Flame Quenching," by A. E. Potter, Jr., and A. L. Berlud, 1955.

This report contains the derivation of a thermal quenching equation in which the rate-controlling reaction is not specified. Two possible rate-controlling reactions are postulated, and the resulting two quenching equations are tested using published quenching data. It is shown that, if the oxygen-fuel reaction is assumed to be rate-controlling, quenching data are satisfactorily correlated for both rich and lean propane-oxygen-nitrogen flames. The pressure dependence of the quenching distance and the relation of quenching distance to burning velocity are also discussed.

THEORY

It is possible to obtain the thermal equation directly from the diffusional equation (if the initial assumption is slightly altered), but it is felt that the derivation presented below is more understandable and allows the assumptions involved to be clearly seen.

For a quenching equation, an initial postulate concerning the conditions under which a flame can exist inside a tube is necessary. A reasonable postulate is as follows: If the heat lost by the flame to the tube walls exceeds a critical value, the flame will be quenched. Since a definite amount of heat is produced in a given flame, an equivalent statement is that, in order for a flame to exist, the heat retained by it must be greater than a critical amount. It will be assumed that this critical amount is a constant fraction of the total heat produced in the flame. The criterion may be written as

$$H_r \geq FH_r \quad (1)$$

(Symbols are defined in the appendix.)

For the combustion of hydrocarbons, complete combustion of the fuel is assumed to occur for all mixture compositions. Consequently, the total heat produced by the process may be written as the product of the mole fraction of fuel in the unburned gas X_f and the heat produced upon the disappearance of 1 mole of fuel ΔH (as defined herein, ΔH is constant and equal to the heat of combustion to CO_2 and H_2O only for stoichiometric or lean mixtures; for rich mixtures, ΔH decreases as the oxygen concentration decreases). Thus, for hydrocarbon flames, equation (1) may be written as

$$H_r \geq FX_f \Delta H \quad (2)$$

The heat retained by the flame can be written in terms of heat capacity and average temperature of the flame in the tube

$$H_r = \bar{C}_p (\bar{T} - T_c) \quad (3)$$

Equation (2) can then be written as

$$\bar{C}_p (\bar{T} - T_c) \geq FX_f \Delta H \quad (4)$$

The average temperature of the flame may be found if it is assumed that heat flow to the walls follows a differential equation of the form

$$(\bar{T} - T_c)'' = \frac{q}{\chi} \quad (5)$$

Here, q is the rate of temperature rise caused by chemical reaction, χ is the thermodiffusivity and primes refer to differentiation with respect to x .

The result of integrating and averaging equation (5) with the boundary condition $\bar{T} = T_c$ at the wall is the equation

$$\bar{T} - T_c = \frac{d^2 q}{G_i \chi} \quad (6)$$

In this equation d is a characteristic dimension of the tube and G_i is a constant associated with the geometric shape of the tube. Derivations of G_i values for various geometries are given in reference 7. Equations (4) and (6) may be combined to give

$$\frac{d^2}{G_i} \geq \frac{FX_f \Delta H \chi}{q} \quad (7)$$

In order for a flame to pass down a tube, the tube size given by d^2/G_i must be equal to or greater than the right side of equation (7). Since the quenching distance is the characteristic tube dimension that just quenches a given flame, equation (7) can be written as a quenching-distance equation by removing the inequality sign;

$$d^2 = \frac{FG_i X_f \Delta H \chi}{q} \quad (8)$$

Then the thermodiffusivity χ can be written as

$$\chi = \frac{\kappa RT}{PC_{p,r}} \quad (9)$$

The rate of temperature rise q can be written as

$$q = \frac{RT \Delta H w}{PC_{p,r} N} \quad (10)$$

Here, w is the rate of disappearance of fuel, molecules per cubic centimeter per second.

Equations (8), (9), and (10) may be combined to give for the thermal quenching equation

$$d^2 = \frac{FG_i N \kappa_r X_f}{C_{p,r} w} \quad (11)$$

The most important fact concerning this equation is that the form for w is not specified; any reaction may be chosen as rate-controlling.

Equation (11) may be derived from the diffusional equation if it is assumed that the thermodiffusivity and diffusion

A THERMAL EQUATION FOR FLAME QUENCHING

289

coefficient are equivalent, and if the criterion for flame propagation is assumed to be that the number of reaction events per cubic centimeter must be a critical fraction of the total number of events that normally occur in the unconfined flame.

In terms of the active-particle—fuel reaction (the reaction specified as rate-controlling in the diffusional equation of ref. 4), the reaction rate w is given by

$$w = k_i a_i \sum c_i, r \quad (12)$$

If a collision-theory-type temperature dependence is assigned to k_i , equation (12) becomes

$$w = B_i a_i \sum c_i, r T_r^{1/2} \exp\left(\frac{-E_i}{RT_r}\right) \quad (13)$$

Combination of equations (10) and (13) gives

$$d^2 = \frac{F G_i N_{K_i} X_i}{C_{x,r} B_i a_i \sum c_i, r T_r^{1/2} \exp\left(\frac{-E_i}{RT_r}\right)} = \frac{F}{B_i} \psi_i \quad (14)$$

The choice of rate-controlling reaction is not limited to the active-particle—fuel reaction. For example, it is possible to follow Semenov (ref. 8) and assume the reaction in the combustion zone to be bimolecular and first-order with respect to fuel and oxygen. For this assumption, the real reacting species are obviously not fuel and oxygen molecules, but such an assumption is satisfactory if the concentrations of the reacting species are proportional to the fuel and oxygen concentrations. In this case, then, the rate of the reaction is given by

$$w = k_i a_i b_i \quad (15)$$

If a collision-theory-type temperature dependence is assigned to k_i , equation (15) becomes

$$w = B_i a_i b_i T_r^{1/2} \exp\left(\frac{-E_i}{RT_r}\right) \quad (16)$$

The combination of equations (10) and (16) gives

$$d^2 = \frac{F G_i N_{K_i} X_i}{C_{x,r} B_i a_i b_i T_r^{1/2} \exp\left(\frac{-E_i}{RT_r}\right)} = \frac{F}{B_i} \psi_i \quad (17)$$

In order to test equations (14) and (17), data for the quenching of propane-oxygen-nitrogen flames were used. These data points include the effect on quenching distance of oxygen-nitrogen ratio, fuel concentration and pressure (ref. 6), and initial temperature (ref. 9).

In order to use equation (14), the assumptions made in reference 4 concerning the active-particle—fuel reaction were followed: T_r was taken to be $0.7 T_p$, the partial pressure of fuel in the reaction zone was assumed to be one-half the

partial pressure of fuel in the unburned gas, the partial pressures of the active particles (H atoms, OH radicals, and O atoms) in the reaction zone were assumed to be 0.7 times their partial pressure in the adiabatic equilibrium flame, and E_i was assumed to be 7 kilocalories per mole (ref. 10).

In order to use equation (17), the partial pressures of fuel and oxygen in the reaction zone were taken as equal to their values in the unburned gas and E_i was assumed to be 38 kilocalories per mole (ref. 11). In keeping with previous usage (refs. 4 and 6), T_r was chosen to be equal to $0.7 T_p$.

The thermal conductivities were calculated for the unburned gas mixture at $0.7 T_p$. The conductivities for oxygen, nitrogen, and propane were calculated at 1553°K , using the tables and data given in chapter 8 of reference 12. Conductivities at other temperatures were computed on the assumption of a $1/2$ -power temperature dependence. The thermal conductivities of the gas mixtures were calculated as the sum of the mole fraction times the thermal conductivity of each component, or,

$$k = \sum X_i k_i \quad (18)$$

It was felt that this simple linear mixing rule was adequate for systems largely composed of nitrogen and oxygen because of their similar conductivities.

The heat capacities were calculated for the unburned gas mixture at $0.7 T_p$ by the same linear mixing rule used for the thermal conductivities. Individual heat capacities for oxygen, nitrogen, and propane were calculated from data given in reference 13.

The equilibrium adiabatic flame temperatures and product compositions were calculated by the matrix method of reference 14 using the thermodynamic constants of reference 14 and the heat of formation of propane given in reference 13.

RESULTS AND DISCUSSION

CORRELATION OF QUENCHING-DISTANCE DATA

Inasmuch as the square of the quenching distance is predicted to be directly proportional to ψ_i (eq. (14)) or to ψ_i (eq. (17)), values of ψ_i and ψ_i were calculated for the pressure, equilibrium adiabatic flame composition and temperature, unburned gas composition and temperature, and tube geometry (assumed to be plane-parallel plates) which correspond to the quenching distances reported in references 6 and 9 for propane-oxygen-nitrogen flames. Plots of d^2 against ψ and ψ_i are shown in figures 1 (a) and (b), respectively. The ranges of the variables included were: pressure, 0.1 to 1.1 atmosphere; equivalence ratio, 0.33 to 1.90; mole fraction oxygen in the oxidant mixture, 0.21 to 0.70; and unburned gas temperature, 300° to 558°K . In figure 1 (a), it is shown that ψ_i (which is entirely analogous to the diffusional equation of ref. 4 except for the choice of quenching criterion) satisfactorily correlates the effect of these variables except for propane-rich mixtures where $\phi > 1.2$.

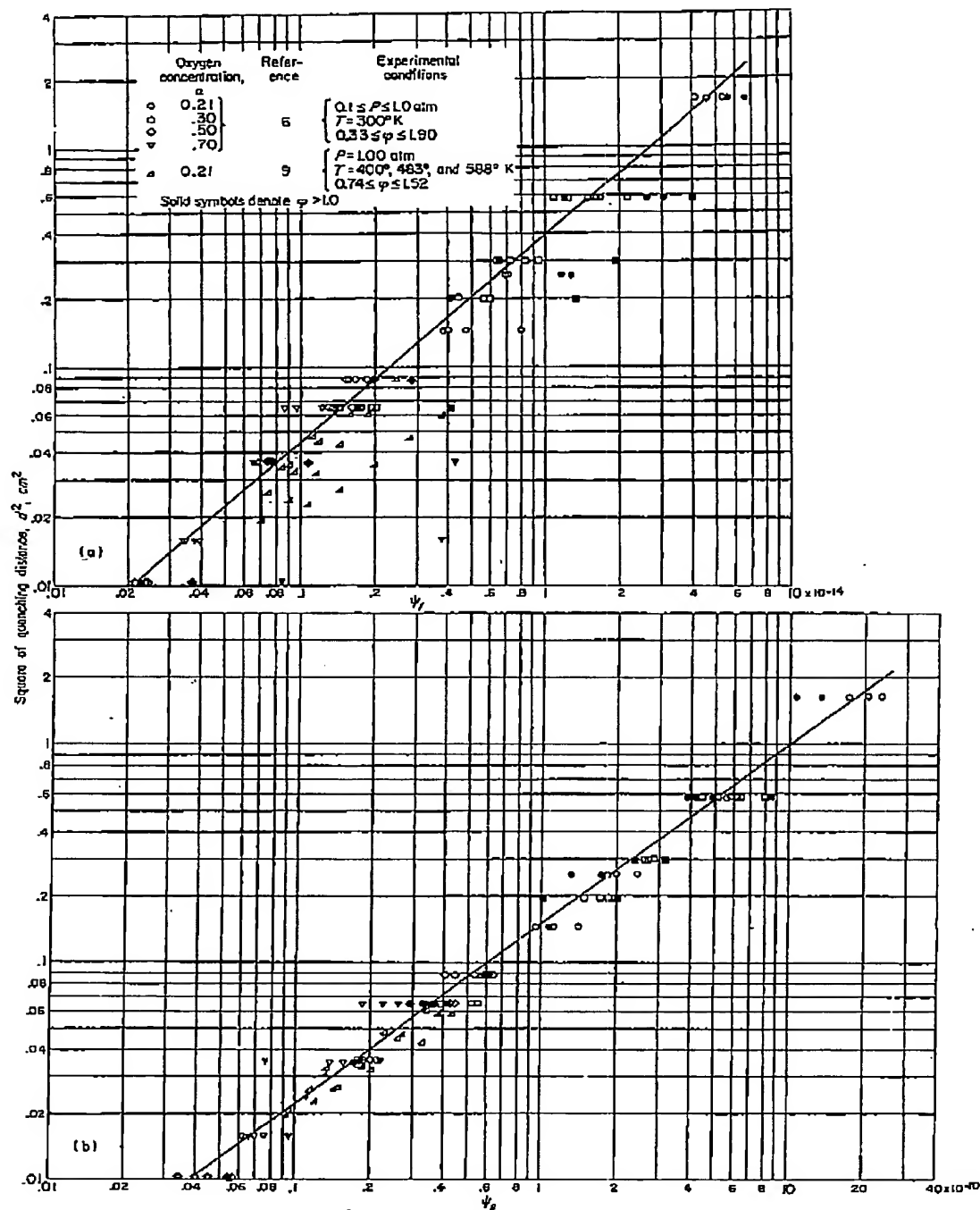


FIGURE 1.—Summary correlations of quenching data by thermal quenching equations.

A THERMAL EQUATION FOR FLAME QUENCHING

29

Inspection of figure 1(b) reveals that ψ , (which includes the oxygen-fuel reaction as the rate-determining step, rather than the active-particle-fuel reaction) correlates not only the propane-lean, but also all the propane-rich quenching data. Thus, it appears that by proper choice of the rate-controlling reaction, the quenching concepts of reference 4 may be extended in such a way as to include rich mixtures for the propane-oxygen-nitrogen system.

The same reaction-rate constants were used for mixtures both rich and lean in propane. This may not be possible for all hydrocarbons; it may be necessary to use different rate constants for rich and lean mixtures, since it is generally believed that the reaction mechanism changes in going from a lean to a rich hydrocarbon flame.

A mean line drawn through the data presented in figure 1 reveals that the predicted linear relation between d^2 and ψ , and ψ , does not hold exactly. Rather, the data are best correlated if $d^2 \propto (\psi)^{0.94} \propto (\psi)^{0.44}$. This difficulty is related, at least in part, to the choice of reaction mechanism, since the "best correlation" exponent is changed by a change in reaction mechanism.

PRESSURE DEPENDENCE OF QUENCHING DISTANCE

Examination of the equation for quenching distance (eq. (11)) reveals that all terms on the right side are independent of pressure except the reaction rate w . However, hydrocarbon flame temperatures change slightly with pressure because of changes in the extent of dissociation. Consequently, a pressure change indirectly affects temperature- and composition-dependent terms in the equation. This effect is quite small, so that the pressure dependence of the quenching distance may be regarded as primarily dependent on the pressure dependence of the initial chemical processes in the combustion wave.

The calculated pressure dependence of the quenching distance (including the indirect effect of pressure on flame temperature and composition) is compared in table I with the experimental values of reference 8. The average deviation of the calculated values from the observed values was found to be 10 percent for ψ , and 17 percent for ψ . Reference 8 gives a value of 7 percent for the average deviation of values computed for the diffusional equation.

It is seen that ψ does not predict the pressure dependence as well as does ψ , except for the high-velocity flames at an oxygen fraction of 0.70. This is probably because the assumption of a simple second-order reaction between fuel and oxygen is a poor one. Concerning prediction of pressure dependence, a better choice of over-all order would be 1.7 rather than 2.0; this is in agreement with theoretical studies of the pressure dependence of burning velocity (ref. 12, p. 765), which indicates that the global reaction in most hydrocarbon flames ranges between first and second order. Such a choice would also tend to improve the linearity of the relation between d^2 (observed) and ψ (calculated).

QUENCHING DISTANCE AND BURNING VELOCITY

The relation of quenching distance to burning velocity has been discussed in references 3, 4, and 15. In reference 4, an

TABLE I.—COMPARISON OF OBSERVED PRESSURE DEPENDENCE OF QUENCHING DISTANCE WITH PREDICTED VALUES

Oxygen fraction, α	Equivalence ratio, ψ	Exponent n describing pressure dependence, $d \propto p^{-n}$			
		Observed	Diffusional	Predicted	
				ψ	ψ
0.17	0.943	0.93	0.83	0.83	1.03
	1.000	.89	.85	.76	1.01
	1.340	.84	.76	.76	1.03
	1.630	.71	.76	.76	1.00
0.21	0.728	0.85	0.86	0.80	1.00
	0.864	.84	.89	.84	1.03
	1.000	.89	.83	.85	1.03
	1.240	.85	.78	.79	1.02
0.35	0.536	0.76	0.87	0.87	1.01
	0.629	.93	.89	.88	1.04
	.773	1.09	.92	.90	1.07
	1.000	.93	.94	.90	1.03
0.40	1.280	.93	.88	.84	1.06
	1.000	.74	.79	.76	1.01
0.60	0.470	1.01	0.91	0.89	1.06
	.644	1.01	.93	.91	1.07
	.680	.86	.86	.85	1.09
	1.000	.93	.97	.93	1.11
0.70	1.363	.91	.95	.90	1.09
	1.940	.89	.88	.81	1.08
0.70	0.245	1.12	0.91	0.89	1.06
	.395	1.12	.93	.91	1.07
	.494	1.03	.86	.85	1.09
	1.000	1.01	.93	.93	1.09
0.70	1.234	1.07	.98	.92	1.11
	1.629	.80	.89	.86	1.08

* Ref. 12.

equation relating the two variables is derived on a purely diffusional basis. The thermal analog to this equation may be derived as follows:

According to reference 16, the Semenov equation for the burning velocity may be written as

$$U = \frac{2\kappa_p \bar{w}}{a_0 \rho_0 c_p} \left(\frac{\eta_1}{\eta_2} \right)^n \left(\frac{\kappa}{D P c_p} \right)^m \quad (19)$$

Multiplying equation (11) by equation (19), converting specific heats to molar heat capacities, and writing a_0 and ρ_0 in the form

$$a_0 = \frac{N X_p P}{R T_0} \quad (20a)$$

$$\rho_0 = \frac{\bar{M} P}{R T_0} \quad (20b)$$

yield

$$d = \frac{R T_0}{U P} \sqrt{\frac{2\kappa_p \kappa_p F G_1 \left(\frac{\eta_1}{\eta_2} \right)^n \left(\frac{R T_0}{D U P} \right)^m \bar{w}}{C_{p,1} C_{p,2} w}} \quad (21)$$

If it is assumed that \bar{w} and w have the same pressure dependence, it follows from equation (21) that, at a given equivalence ratio,

$$U \propto \frac{1}{P} \propto P^{-(n+1)} \quad (22)$$

From reference 6, it is seen that n decreases from about -0.9 to -1.05 as the percent oxygen in the oxidant mixture is increased from 21 to 70. Simultaneously, the burning velocity increases from about 40 centimeters per second to the order of 300 centimeters per second. Consequently, equation (22) predicts that the exponent describing the pressure dependence of U should increase from about -0.1 to 0.05 as U increases from 40 centimeters per second to about 300 centimeters per second. This result may be compared with the experimental findings of Lewis (ref. 17) (which indicate an increase of about -0.05 to 0.07 as burning velocity changes from 40 to 300 cm/sec) to confirm equation (22) qualitatively.

CONCLUDING REMARKS

The fact that reasonable agreement exists between experiment and quenching concepts based on either heat or mass transfer indicates only that these processes have the same formal laws and that the thermal and molecular diffusivities are either equal or remain directly proportional for the data considered in this study. No evidence for the preponderance of either heat or mass transfer in quenching can be deduced from these results. The principal advantage gained by formulation of the quenching concepts of reference 4 in a "thermal" form is that a change in reaction kinetics is much simpler from a conceptual point of view for the "thermal" form than for the "diffusional" form. This conceptual advantage might be useful in a discussion of bizarre fuel-oxidant systems for example, CS_2 - F_2 flames. In addition, the actual calculations may be simplified, since by the proper choice of reaction mechanism, it may become unnecessary to calculate the equilibrium flame composition.

SUMMARY OF RESULTS

The results of an investigation into the possibility of extending quenching concepts previously proposed to include quenching of hydrocarbon-rich flames may be summarized as follows:

1. An equation for the critical quenching configuration of a channel was derived for hydrocarbon flames:

$$\bar{d}^2 = \frac{FG_d N \kappa_u X_f}{C_{p,r} \Delta T}$$

where

$C_{p,r}$	heat capacity in reaction zone, cal/(°K) (mole)
\bar{d}	characteristic dimension of tube geometry; quenching distance, cm
F	constant that relates total heat produced by combustion to heat which must be retained by flame for it to exist
G_d	dimensionless factor, dependent only on channel geometry
N	Avogadro's number
w	rate of reaction in reaction zone, molecules/(cc) (sec)
X_f	mole fraction of fuel in unburned gas
κ_r	mean thermal conductivity in reaction zone, cal/(cm) (sec) (°K)

2. Two possible flame-initiating reactions were considered in the detailed formulation of w : (1) the reaction between active particles and fuel molecules, and (2) the reaction between oxygen and fuel molecules.

3. The two equations resulting from the two reaction mechanism choices were tested using published data that included the effect of oxygen-nitrogen ratio, fuel concentration, pressure, and unburned gas temperature on the quenching distance for propane-oxygen-nitrogen flames. These variables were correlated reasonably well for both rich and lean flames by the equation involving the oxygen-fuel reaction. The equation involving the active-particle-fuel reaction was satisfactory primarily for lean flames.

4. It was concluded that, by the proper choice of reaction kinetics, the quenching concepts previously proposed may be cast in a form useful for the prediction of both propane-rich and -lean quenching data.

LEWIS FLIGHT PROPULSION LABORATORY

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
CLEVELAND, OHIO, December 6, 1954

APPENDIX

SYMBOLS

The following symbols are used in this report:

a	fuel concentration, molecules/cc
B	Arrhenius constant
b	oxygen concentration, molecules/cc
C_p	heat capacity, cal/(°K) (mole)
$\bar{C}_{p,r}$	average heat capacity, T_0 to T_r , cal/(°K) (mole)
c_i	concentration of i th active particle, molecules/cc
c_p	specific heat, cal/(°K) (g)
\bar{c}_p	average specific heat, T_0 to T_r , cal/(°K) (g)
D	diffusion coefficient, sq cm/sec
d	characteristic dimension of tube geometry; quenching distance, cm
E	activation energy, cal/mole
F	constant that relates total heat produced by combustion to heat which must be retained by flame for it to exist
G	dimensionless factor, dependent only on tube geometry
ΔH	heat released upon consumption of 1 mole of fuel by combustion process, cal/mole
H_r	heat produced by chemical reaction in primary reaction zone, cal/mole
H_T	total heat produced by combustion of 1 mole of unburned gas, cal/mole
k	rate constant, (cc) (molecules)/sec
M	average molecular weight of unburned gas, g/mole
m	molecularity of flame reaction
N	Avogadro's number
n	exponent describing pressure dependence of quenching distance
n_1/n_2	moles of reactant per moles of product from stoichiometric equation
P	pressure, atm
q	rate of temperature rise, °K/sec
R	gas constant
T	temperature, °K
U	flame speed, cm/sec
\bar{W}	average reaction rate in flame front as defined by Semenov, molecules/(cc)(sec)
w	reaction rate in reaction zone, molecules/(cc)(sec)
X_r	mole fraction of fuel
x	distance, cm
α	mole fraction of oxidant in oxidant-inert mixture
κ	thermal conductivity, cal/(cm)(sec)(°K)
ρ	density, g/cc
ϕ	equivalence ratio
χ	thermodiffusivity, sq cm/sec
ψ_r	$\frac{G_r N_r X_r}{C_{p,r} a_r b_r T_r^{1/2} \exp \left(\frac{-E_r}{RT_r} \right)}$
ψ_i	$\frac{G_i N_i X_i}{C_{p,i} a_i \sum c_i T_i^{1/2} \exp \left(\frac{-E_i}{RT_i} \right)}$
Subscripts:	
r	flame
i	active-particle species

o	unburned gas
r	reaction zone
s	involves reaction of oxygen and fuel molecules
t	involves reaction of active particles and fuel molecules

REFERENCES

1. von Kármán, Theodore, and Millán, Gregorio: Thermal Theory of a Laminar Flame Front Near a Cold Wall. Fourth Symposium (International) on Combustion, The Williams & Wilkins Co. (Baltimore), 1953, pp. 173-177.
2. Rosen, J. B.: Theory of Laminar Flame Stability. I—Analytic Stability Condition. Jour. Chem. Phys., vol. 22, no. 4, Apr. 1954, pp. 732-748.
3. Lewis, Bernard, and von Elbe, Guenther: Combustion, Flames and Explosions of Gases. Academic Press, Inc. (New York), 1951.
4. Simon, Dorothy M., Belles, Frank E., and Spakowski, Adolph E.: Investigation and Interpretation of the Flammability Region for Some Lean Hydrocarbon-Air Mixtures. Fourth Symposium (International) on Combustion, The Williams & Wilkins Co. (Baltimore), 1953, pp. 126-135.
5. Friedman, Raymond, and Burke, Edward: Spark Ignition of Gas Mixtures. Jour. Chem. Phys., vol. 17, no. 7, July 1949, p. 667.
6. Berlad, A. L.: Flame Quenching by a Variable-Width Rectangular-Channel Burner as a Function of Pressure for Various Propane-Oxygen-Nitrogen Mixtures. Jour. Phys. Chem., vol. 58, no. 11, Nov. 1954, pp. 1023-1028.
7. Berlad, A. L., and Potter, A. E., Jr.: Prediction of the Quenching Effect of Various Surface Geometries. Fifth Symposium (International) on Combustion, Reinhold Pub. Corp., 1955, pp. 728-735.
8. Semenov, N. N.: Thermal Theory of Combustion and Explosion. III—Theory of Normal Flame Propagation. NACA TM 1026, 1942.
9. Friedman, Raymond, and Johnston, W. C.: The Wall-Quenching of Laminar Flames as a Function of Pressure, Temperature and Air-Fuel Ratio. Jour. Appl. Phys., vol. 21, no. 8, Aug. 1950, pp. 761-795.
10. Tanford, Charles: The Role of Free Atoms and Radicals in Burner Flames. Third Symposium on Combustion and Flame and Explosion Phenomena, The Williams & Wilkins Co. (Baltimore), 1949, pp. 140-146.
11. Jost, Wilhelm: Explosions and Combustion Processes in Gases. McGraw-Hill Book Co., Inc., 1946, p. 437.
12. Hirschfelder, Joseph O., Curtiss, Charles F., and Bird, R. Byron: Molecular Theory of Gases and Liquids. John Wiley & Sons, Inc., 1954.
13. Rossini, Frederick D., et al.: Selected Values of Properties of Hydrocarbons. Circular C461, Nat. Bur. Standards, Nov. 1947.
14. Huff, Vard N., Gordon, Sanford, and Morrell, Virginia E.: General Method and Thermodynamic Tables for Computation of Equilibrium Composition and Temperature of Chemical Reactions. NACA Rep. 1037, 1951. (Supersedes NACA TN's 2113 and 2181.)
15. Friedman, Raymond: The Quenching of Laminar Oxyhydrogen Flames by Solid Surfaces. Third Symposium on Combustion and Flame and Explosion Phenomena, The Williams & Wilkins Co. (Baltimore), 1949, pp. 110-120.
16. Dugger, Gordon L., and Simon, Dorothy M.: Prediction of Flame Velocities of Hydrocarbon Flames. Fourth Symposium (International) on Combustion, The Williams & Wilkins Co. (Baltimore), 1953, pp. 338-345.
17. Lewis, Bernard: Selected Combustion Problems. Fundamentals and Aeronautical Applications, Butterworths Scientific Pub. (London), 1954, pp. 170-177.